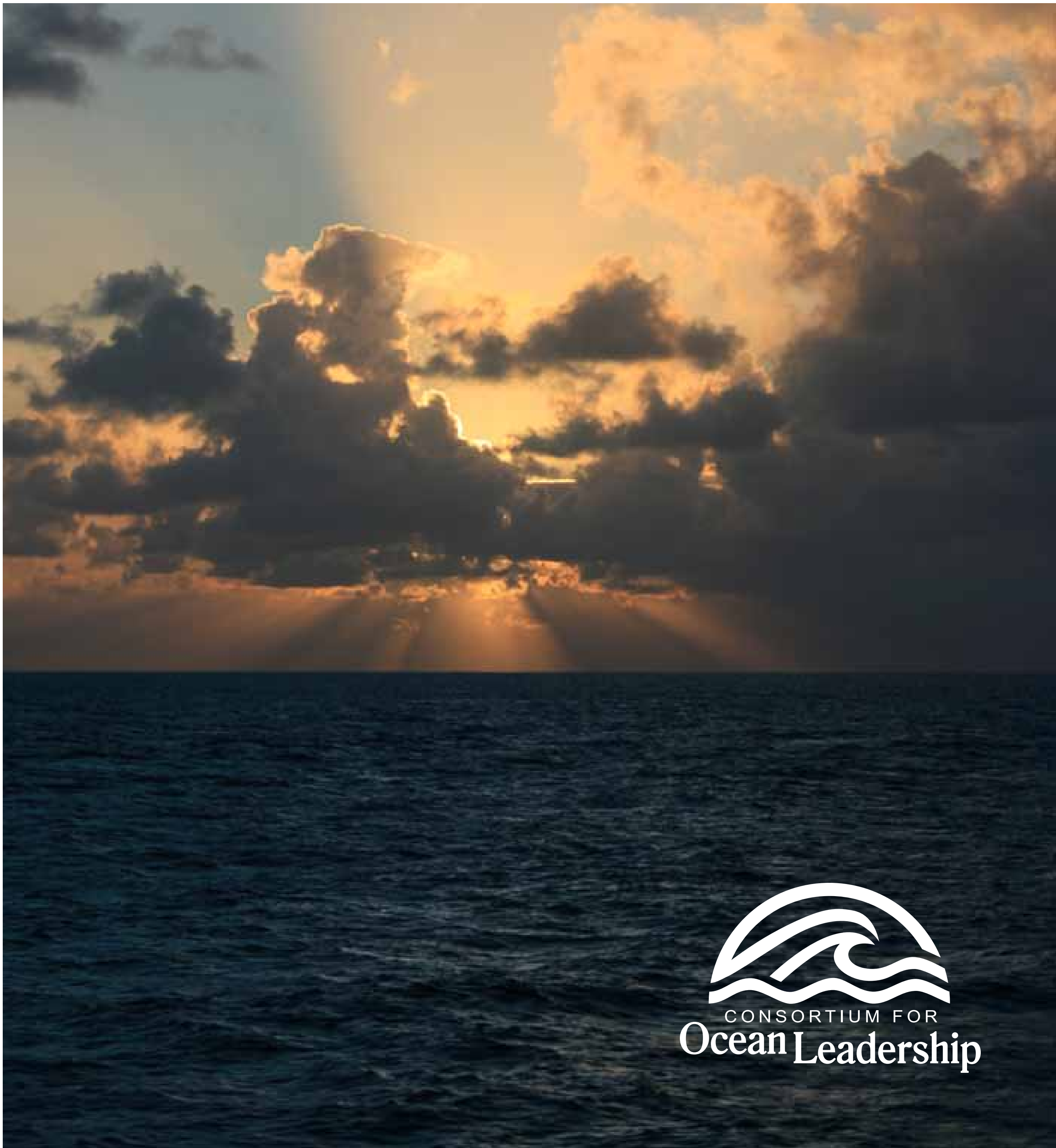
DECIPHERING THE OCEAN CLIMATE SYSTEM



CONSORTIUM FOR
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The Consortium for Ocean Leadership is a Washington, D.C.-based nonprofit organization that represents 94 of the leading public and private ocean research and education institutions, aquaria and industry. Ocean Leadership's mission is to advance research, education and sound ocean policy.

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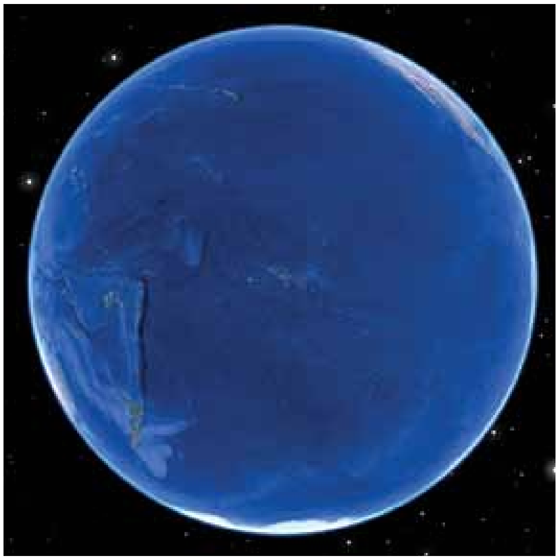

THE OCEAN is the predominant physical feature on our planet, covering 72 percent of the Earth's surface. The ocean's role in the climate system is equally influential as it absorbs, retains and transports vast amounts of the Earth's heat, water and carbon dioxide across the globe. In fact, just the top ten feet of the ocean holds as much heat as the entire atmosphere. Beyond driving the climate system, the ocean itself is being affected by a rapidly changing environment. Ocean waters are warming and becoming more acidic, ocean currents are shifting, and sea levels are rising, all of which have significant implications for our economy, the health of our oceans and human society. While we know the climate and our oceans are changing, we have very limited capacity to accurately forecast the size, scope and time scales for these alterations.

There are three critical oceanic areas that require significant new scientific investments for improving our ability to understand, assess and adapt to a changing planet and manage our resources wisely. These include changes in ocean productivity, sea-level rise, and the opening of the arctic system. Robust remote and in situ monitoring systems, basic and mission oriented research, and improved modeling capabilities are needed if we are to meet the complex challenges facing society from an ocean system that may transition into a state enormously different than any other during the history of human civilization.

CHANGES IN OCEAN PRODUCTIVITY

The ocean has adjusted to countless natural cycles of climate change of tectonic, astronomical, oceanographic, and other origins over the ages, and yet for most of that time remained healthy and productive. In fact, the carbon dioxide (CO_2) concentration in the atmosphere has not been substantially higher than it is now for at least the last 20 million years. Furthermore, the Earth's climate has been comparatively stable for the last 12,000 years during which time humans have thrived. What differs with the present period of human induced climate change is first the rate and amount of (CO_2) discharge, which is so rapid and so large that natural oceanic buffering mechanisms that might mitigate some of the worst consequences cannot keep pace. Second, the effects of burning of fossil fuels, namely global warming and ocean acidification, are compounded by two other major human impacts: over-fishing and eutrophication (creation of dead zones caused by excess nutrients from agricultural and urban runoff). These cumulative effects make it difficult to separate from the influence of any one factor alone in time. Furthermore, the lack of information on complex interactions in ocean and coastal ecosystems impede precise predictions on the short- and long-term impacts of climate change on future ocean productivity.

The impact that is evident is that overfishing and associated marine habitat destruction has reduced marine biodiversity. Less diverse ecosystems are less resilient to the types of stress that the ocean is currently facing with global warming, ocean acidification, and the reduction in oxygen associated with eutrophication. Moreover, these pressures are affecting the ocean's role in biogeochemical cycles, including carbon and nitrogen. These changes have already and will continue to dramatically alter the productivity of our oceans.

Increasing CO_2 content in the atmosphere is having both direct and indirect effects on ocean ecosystems. The most noticeable direct impact

is the lowering of ocean pH levels - "ocean acidification" - resulting from the ocean having absorbed almost a third of the CO_2 produced by the burning of fossil fuels. While this process has helped buffer the accumulation of atmospheric CO_2, the result has been a very high rate of change in ocean chemistry. The acidity of the oceans has increased by 30 percent since the beginning of the industrial revolution and numerous studies are underway to assess its impact on ocean ecosystems. Many marine organisms rely on calcium carbonate to build their shell exoskeleton, and an increasingly acidic ocean will greatly reduce their ability to make these essential structures. These changes will have significant impacts on the entire marine food web.

Increasing CO_2 continues to have a wide range of indirect impacts on ocean ecosystems through processes associated with climate change. Shifts in winds over the ocean, increasing temperatures, and changes in precipitation are altering the supply rates of deep-ocean nutrients to the upper ocean. Behrenfeld et al. (2006) have detected a global-scale decline in ocean productivity through an analysis of satellite-measured ocean chlorophyll, which they attribute to changes in nutrient supply. Coastal ecosystems, which account for about 10 percent of the ocean's primary productivity and much of its commercial fisheries, are being affected by changes in coastal watersheds and also by the ocean's response to global warming. For example, earlier snowmelt in the Pacific Northwest is impacting the timing of nutrient inputs to the coastal ocean as well as migration of juvenile salmon from rivers to the ocean.

The ocean's responses to these changes are as varied as the complex processes that drive Earth's climate. Warmer temperatures lead to coral bleaching and favor the northward expansion of jellyfish populations into the Bering Sea. Shifts in the position of the atmosphere's jet stream are also suspected to stimulate the formation of hypoxic zones off the Pacific Northwest coast. Thus the structure and composition of ocean ecosystems are changing, which is influencing its overall productivity and capacity to provide benefits and services for society.

Against the background of climate change, ocean ecosystems have been subjected to decades of intense fishing, urban and agricultural runoff, and the loss and degradation of estuaries and wetlands. Worm et al. (2006) describes the declines in biodiversity and changes in population size structures and the resultant impacts on marine ecosystems. Invasive species from ballast water release, accidental species introductions, and aquaculture are additional pressures on ocean ecosystems. Massive amounts of nitrogen have been "fixed" from the atmosphere to manufacture fertilizer for agriculture, and the human impact on the global nitrogen cycle is as profound as the impact of fossil fuel combustion on the global carbon cycle. The result is that ocean ecosystems have been degraded and are not as resilient in the face of the stresses accompanying climate change.

Life in the deeper ocean is perhaps the most threatened by a combination of increasing carbon dioxide and decreasing oxygen concentrations. The amount of dissolved carbon dioxide is increasing because the oceans are absorbing more carbon dioxide from the atmosphere. At the same time, ocean surface waters are warming and becoming more stratified, which allows less oxygen to be transported vertically into the depths. Brewer and Peltzer (2009) quantify the impacts of these multiple stressors on marine organisms with the concept of a "respiration index." This index is based on the ratio of oxygen and carbon dioxide gas in a given sample of seawater. The lower the respiration index, the harder it is for marine animals to respire. Tracking changes in the respiration index helps marine biologists understand and predict which ocean waters are at risk of becoming dead zones in the future. The most severe effects will take place in the "oxygen minimum zones." These are depths, typically 300 to 1,000 meters below the surface, where oxygen concentrations are already quite low in many parts of the world's oceans. For example, if current trends of oxygen depletion continue, highly productive coastal upwelling zones such as Monterey Bay will cease to support any oxygen-breathing organisms at depths between 300 and 800 meters in just 35 years.

The processes of climate change as well as fishing, fertilizer production, and other human activities will continue, and their impacts will likely increase. Moreover, new pressures on our oceans will emerge. River flows will be increasingly exploited for both water and hydropower so that more rivers will no longer reach the ocean, which is the case for the Colorado River today. Wind and wave energy farms in coastal waters will affect ocean processes and hence marine ecosystems. At-sea aquaculture will become more common, with increased possibilities for release of invasive species and diseases. The concentration and accumulation of pharmaceuticals accompanying human wastewater is impacting reproductive capacity of many marine ecosystems. Construction of desalinization plans to provide freshwater to growing human populations will introduce warm, salty water as well as pollutants into coastal ecosystems. New types of ocean management and "geoengineering" will emerge, such as marine protected areas to preserve entire ecosystems, and iron fertilization and artificial upwelling as carbon sequestration mechanisms are being considered.

The sustainability of ocean ecosystems will be driven by a combination of local and global-scale processes through a complex, interacting coupling of ocean, atmosphere, and land processes. And sustainability will not be measured simply as the level of ocean productivity but also as the resilience of ecosystem structure and processes. Increasing demands and pressures on oceans and coasts, including renewable energy development and impacts associated with climate change, requires a new approach to ecosystem management. This requires new levels of investment in ocean science and its supporting infrastructure to provide decision makers and society with the knowledge and information to understand and sustainably manage our ocean ecosystems.

OPENING OF THE ARCTIC SYSTEM

The Arctic region is of great strategic importance to our society. The Arctic harbors tremendous natural resources, a thriving and productive natural ecosystem, which is increasingly becoming an international focus for expanded navigation and commerce. The Arctic region is also highly sensitive to changes in climate. Because of its high latitude, effects of climate change are amplified relative to other regions. Rapid warming and the loss of sea ice in the Arctic are well documented and the impact of such changes on marine and terrestrial ecosystems in the Arctic and beyond will be profound.

Climate projections for the Arctic region depend on knowing the state and circulation of the Arctic Ocean, yet ocean-ice interactions are poorly understood. The Arctic basin is insufficiently instrumented for real-time observations, and there is a need for improved integration of observations into models to produce reliable projections.

Despite its remoteness, the Arctic Ocean plays a pivotal role in Earth's climate system. The presence of extensive summer sea ice strongly influences the earth's energy budget because, by its very nature, ice reflects approximately 90 percent of the incoming energy from the sun. Meanwhile the ocean absorbs about the same amount of solar energy. Thus, the loss of this reflective cover creates a positive feedback loop. The extent of summer sea ice has been in steady decline for approximately fifty years, surpassing even the most pessimistic climate model predictions. There are now projections for significant and abrupt declines in summer sea ice extent over the next several decades. The decline in ice extent has been accompanied by a significant decrease in the thickness of the sea ice.

The reality of recent changes in the Arctic—rapid warming and the accelerating loss of sea ice—is now widely acknowledged and the impact of such changes on marine and terrestrial ecosystems in the Arctic and beyond will be profound. The Arctic region encompasses a highly productive ecosystem, the function of which is intimately coupled to the seasonal dynamics in sea ice extent and the associated meteorological conditions and water properties. There is already evidence that trends in sea ice extent and duration in the Arctic region have negatively impacted some species. Such declines in key species have also threatened indigenous human cultures whose economies and way of life depend on hunting for survival. The strategic importance of an ice free Arctic is driving territorial claims for the Arctic sea floor; speculation of increased commercial shipping, and increased exploration for fossil fuel and other resources on the broad Arctic shelves.

The ocean's role in the formation of sea ice and its melting is a crucial element in quantifying and projecting the future rates of melting. By exposing the ocean surface to direct sunlight, the loss of sea ice causes a warming of the ocean surface which makes it more difficult to freeze during the subsequent colder seasons. In addition, exposing the ocean surface to harsh Arctic winds causes vertical mixing of the upper ocean water column, breaking down the strong vertical gradients in sea water density that allow ice to form in the first place. Our ability to forecast sea ice extent and thickness on seasonal and decadal time scales relies on monitoring ocean properties throughout the Arctic basin. The presence or absence of sea ice will determine the rate and magnitude of the future warming of the Arctic region. It is of utmost importance to establish a comprehensive observing system in the Arctic to monitor the extent of the sea ice, the thickness of the sea ice and the structure and properties of the water column immediately beneath the sea ice.

FORECASTING & ADAPTING TO SEA-LEVEL RISE

Accelerated sea-level rise is perhaps the most concerning ocean-related consequence of climate change because it is seen as a direct threat to property, infrastructure and public safety. Global average sea level rose by 17 cm (6.7 inches) during the 20th century, following a long period of years of relatively stable sea level. By the end of the century global sea-level rise had accelerated to 0.31 cm/yr based on satellite altimeter measurements. Locally, of course, the level of the sea relative to the land (or relative sea level) varied by greater or lesser amounts depending on the vertical movements of the land mass. In some subsiding coastal areas, relative sea level rose by 0.70 meters (two feet) or more during the past century. Also, sea level does not rise uniformly throughout the oceans as a result of differential warming and redistribution of mass, further complicating the ability to forecast future sea level for any given coastal region in the world.

Global average sea level is rising as a result of the thermal expansion of warming ocean waters, the melting of glaciers and ice caps, the melting of polar ice sheets on Greenland and Antarctica, and changes in terrestrial water storage. The IPCC Fourth Assessment published in 2007 took a conservative approach and excluded changes in polar ice sheet dynamics in estimating sea-level rise during the 21st century, projecting a rise of 0.2-0.4 meters (0.6-1.2 feet) under a low greenhouse gas emissions scenario and 0.3-0.6 meters (0.9-1.9 feet) under a high emissions scenario. Post-IPCC analyses have shown that the contribution to sea-level rise of the melting of polar ice sheets dramatically increased from 2003 to 2008 and exceeded the contribution of thermal expansion. Additional efforts to estimate sea level rise during this century based on empirical relationships with temperature or potential ice melting suggest that it is likely to exceed IPCC estimates and reach 1.3 meters, with considerable uncertainty on the upper limit. Some leading analysts believe that sea-level rise of 1 meter during this century is not only possible but likely. Furthermore, sea level will continue to rise for centuries even after greenhouse gas concentrations are stabilized as an irreversible consequence of climate change.

Sea level may rise as little as 0.6 feet or as much as 5 feet. This uncertainty regarding sea-level rise may not appear significant in contrast to the average depth of the ocean, but it has major consequences with regard to the impacts on coastal environments, communities and infrastructure. Keep in mind that the sea-level rise that has already occurred and will be experienced is unprecedented during modern civilization. For the several hundred years prior to the industrial revolution, global sea level rose only slightly. During this period present shorelines and wetlands were formed, communities were established and infrastructure was built.

Sea-level rise will not only affect shoreline erosion and inundate low-lying lands, but it will also exacerbate the risks of storm surges -- a one in 100 year flooding event would occur annually with just a 0.5 meter rise in mean sea level in many regions. Most of the nation's coastal wetlands will be eliminated or forced landward as sea level rises; their survival will depend on supplies of remobilized sediments that allow vertical soil accretions. Rising sea level will also increase the penetration of salinity into estuaries, thus affecting their circulation, biota and resources, and salt water infiltration of coastal aquifers.

There is a pressing need for greater certainty in sea level projections to guide managing appropriate coastal development and formulate effective adaptation plans. The economic and social stakes are enormous. Extensive areas, including South Florida, coastal Louisiana, the San Francisco Bay Delta, and much of eastern North Carolina would be inundated by a three foot rise in sea level. In the Gulf Coast area alone, an estimated 2,400 miles of major roadway and 246 miles of freight rail lines would be at risk from permanent flooding if global warming and land subsidence combine to produce a relative sea-level rise of four feet.

SCIENCE GAPS / WHAT SOCIETY NEEDS

The success of any attempt to monitor, quantify and predict changes in the global carbon cycle and its impact on the climate system will require a comprehensive plan for observing the earth, ocean and atmosphere. The weakness in existing climate and weather models are often found in the ocean system, which is poorly monitored and lacks the *in situ* observing systems necessary to track the global transfer of carbon, heat and water horizontally and vertically, and ground truth observations from remote (satellite) systems.

As we struggle to restore the health of our ocean ecosystems as well as derive more services from them, climate change has added considerable pressure and uncertainty to our decision making. We need plausible scenarios regarding the future state of ocean ecosystems to highlight areas of vulnerability as well as "transition" thresholds. Simply "reducing uncertainty" is not sufficient. Society is making decisions now, and we cannot expect to wait until the scientific community has substantially reduced uncertainty regarding climate change. We desperately need to monitor the ocean for the continuing impacts of climate change. Furthermore, the effectiveness of climate policies and ecosystem management strategies can only be assessed through sustained ocean observations. Lastly, we need to understand the impacts of extreme

events that result from climate change such as tropical storms or the disappearance of summer ice in the Arctic Ocean.

To accomplish these goals, our nation will need to make significant investments to obtain and integrate real-time data from space and *in situ* sources, in basic research to elucidate ocean-atmosphere dynamics, and in mission oriented research to help forecast ecosystem responses to a rapidly changing environment. It is essential that this information is converted into products and services that are delivered in timely fashion to managers, policy makers and the public.

OBSERVING SYSTEM REQUIREMENTS

The oceans are the missing piece of the climate puzzle. The National Academies in its 2009 report, "Restructuring Federal Climate Research to Meet the Challenges of Climate Change" identified the establishment of a U.S. climate observing system as a top priority. It noted that both ground and remote sensing systems are in decline even as demand for data is growing. Thus, in order to understand, model, and forecast global and regional climate systems, the United States needs to develop, support and sustain a global ocean observing system. This system requires observations from both space, on and below the ocean surface, and a capability to effectively integrate data.

RESEARCH PRIORITIES

a. ARCTIC DYNAMICS - Understand the oceanographic processes that weaken the halocline and monitor stratification across the Arctic Ocean to see if the halocline is eroding. Decipher the air-sea interactions that cause the Beaufort Gyre to alternately accumulate fresh water and release it to the rest of the ocean, and monitor how the system may be changing. Learn how changes in the Arctic ice cover are affecting the ecosystem from the microscopic algae, to copepods, fish, whales and other marine mammals, and finally, to humans.

b. Quantify ocean warming and its effect on ocean volume and, in particular, the processes governing the melting of polar ice sheets. It is becoming increasingly clear that ice sheet dynamics are greatly influenced by regional oceanographic conditions and the extent of sea ice.

c. OCEAN ACIDIFICATION - Initiation of a comprehensive program to monitor, understand and predict the impacts of ocean acidification on ocean ecosystems. As part of the U.S. Carbon Cycle Science Program, a program should be developed to study ecosystem responses to ocean acidification, especially for those systems that are under stress from human and climate change impacts. Further, the program should focus on the interplay between ecosystems and biogeochemical cycling in an increasingly acidic ocean.

d. Long-term, integrated process studies of Large Marine Ecosystems (LME) - With a new emphasis on ecosystem-based approaches to management, new research programs should be initiated, relying on effective university/agency partnerships. These programs should develop a core set of observing and modeling systems, with the ability to add special-focus programs over time, such as monitoring the impact of marine protected areas or renewable energy development. The CalCOFI program is one such model, but other regions (including the open ocean) need similar long-term, extensive observing and research programs. New Long-Term Ecological Research sites - NSF's LTER program has been very successful, but it generally focuses on terrestrial or marine systems separately. New opportunities should be developed that link coastal ocean and terrestrial watershed ecosystems. Particular emphasis should be given to those areas strongly affected by urban processes.

e. Effects on coastal environments of sea-level rise together with changes in temperature, precipitation and storms, must be better understood to allow their effective management and provide the foundation for adaptation strategies. Such effects are not limited to shorelines and wetlands, but extend to tidal and other currents.

f. Strategies to adapt to sea-level rise are truly in their infancy. Assessments of vulnerability and socio-economic consequences are required. Opportunities exist for the design of new infrastructure systems that are resilient, sustainable, and effective in minimizing greenhouse gas emissions.

REMOTE SENSING PRIORITIES

No single U.S. federal agency is committed to an effective strategy for long-term data acquisition from space in support of science. Our present constellation is a mix of research-driven, fixed duration missions and satellites focused on operational weather prediction. Moreover, we need an integrated set of observations of physical and biological processes of both ocean and atmosphere. In fact, there are no plans in place to measure ocean color (as a measure of ocean biomass and productivity) and vector winds (scatterometry) over the ocean from space. The following list highlights the science needs to understand long-term changes in climate and ecosystems which present systems will not meet.

a. Development of an altimetry mission (*Jason-3*) to provide ocean surface topography data, which will quantify water movement through the ocean and air-sea energy exchanges as well as identify changes in sea level. Extending observations of global sea-level rise beyond the existing *Jason-2* mission will require that a *Jason-3* be available for launch in 2013 so that it can overlap with *Jason-2* before the latter reaches the end of its design life.

b. Development of an operational Duel-Frequency Scatterometer (DFS) providing sea surface vector wind measurements. The DFS is a microwave radar that has the capability to observe the surface vector wind field over the global oceans, building on the success realized over the past decade by NASA's QuikSCAT. The two channels of the DFS, unlike existing instruments, have the capability to resolve high winds from rain, crucially needed to observe the fine structure of the winds associated with hurricanes and winter storms. Without the DFS, the U.S. will not have the capacity to collect observations of the global wind field in the post-QuikSCAT era.

c. Development of a science-quality ocean color satellite mission. A global-scale ocean color mission was not included in the NRC Decadal Survey as it was assumed that NPOESS/VIIRS would meet the needs of the climate science community. This is not the case; a new approach needs to be developed in order to prevent a substantial gap in ocean color measurements. Planning to make effective use of non-U.S. data, a substantive calibration and validation program to ensure continuity of the observing record, as well as development of a new global-scale mission to measure ocean color are needed.

IN SITU SENSING PRIORITIES

a. The Arctic region requires a full-time observation system (an integrated Arctic Observing Network) to monitor atmosphere-ice-ocean interactions. Furthermore, an integrated data-model capacity is needed to utilize these observations for seasonal to decadal projections of sea ice and regional climate over the ocean and surrounding land masses. Historically, the Arctic region's ice cover, remoteness, seasonal darkness, and extreme weather have made it very difficult for researchers to establish observatories in the Arctic. However, there are now a significant number of new, autonomous systems and platforms capable of working in this harsh environment. These observation systems should be built to further our capabilities to:

   - Monitor the extent of fresh water exiting the Arctic into the North Atlantic, which could disrupt Atlantic and global circulation and lead to more extensive climate change.
   - Monitor and analyze melting patterns on Greenland to determine the stability of the ice sheet and its susceptibility to rapid disintegration.
   - Determine the extent and effects of melting permafrost.

b. Deployment and integration of a suite of ocean biology and chemistry measurements into on-going, *in situ* observing systems such as IOOS, Argo and OOI is needed. With limited budgets, both IOOS and Argo have focused on spatial coverage (e.g., development of regional associations to cover US coastal waters), relying on essential physical measurements. New sensors to measure ocean biology and chemistry (including pH) need to be developed and deployed as soon as possible for both monitoring and prediction.

c. Monitoring of sea level will require an expanded system of advanced water level measurements and sustained satellite measurements of altimetry and gravimetry. These measurements must be integrated to account for global trends and regional differences due to geodesy, currents, water mass distribution, and variations on scales from seasons to decades.

SUMMARY

Our nation needs to take bold action to be the world leader in climate science. Our oceans are facing a multitude of perturbations not seen in millions of years, perhaps ever. Science must play a critical role informing wise policy and management decisions. Furthermore, policy needs to adapt to changing scientific discoveries and shifting ecosystems. Our capacity to predict and reduce risks requires significant scientific investments and coordination across agency, state, and national boundaries. We need an ocean equivalent of the weather service – with a fully implemented physical forecast system (waves, currents, tides, swell, surge, etc.) and expanded to include chemistry and biology as sensors are developed.

The existing patchwork of federal agencies, programs and initiatives is insufficient to meet the growing demand for information for decision makers. No single federal agency has the mission, ability or resources to develop, build and maintain the required architecture for a sustained, long-term, global climate observing and science system. The need is clear, the desire exists, yet the goal can only be reached by granting the Office of Science Technology Policy the budget authority to develop, request and manage a dedicated climate observation and science budget.

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